TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 305

CORROSION EMBRITTLEMENT OF DURALUMIN

VI. THE EFFECT OF CORROSION, ACCOMPANIED BY STRESS, ON THE TENSILE PROPERTIES OF SHEET DURALUMIN

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Light aluminum alloys of the duralumin type, that is, high-strength wrought alloys whose properties can be improved decidedly by heat treatment, are of very great importance, especially in the form of sheet and tubes, for aircraft construction. The permanence of such materials when exposed to corrosive conditions such as may obtain in aircraft service should be known, however, with a high degree of certainty and precautionary measures taken to guard against any possible serious deterioration in service. To obtain reliable information along this line, an investigation, the results of which form the basis of this series of reports (Reference 1), has been carried out at the Bureau of Standards in cooperation with the National Advisory Committee for Aeronautics, Bureau of Aeronautics of the Navy Department, and Army Air Corps. The leading manufacturers have also participated in the investigation by furnishing practically all of the materials needed. The investigation, which was started in the latter part of 1925, is still in progress, and final and complete answers have not yet been reached on all points concerning the permanence of sheet duralumin in service.

The information which has been obtained, however, is of very considerable value to both manufacturers and users of aircraft and its publication at this time would seem to be warranted although possibly some of the statements made may be modified slightly in the light of future results.

I. Introduction

In the preceding reports in this series (Reference 1), the effects of corrosive influences on the mechanical properties of sheet duralumin have been discussed at considerable length. It has been shown that the embrittlement of materials of this type which has been encountered at times in service can be duplicated in the laboratory by suitable accelerated corrosion tests and the validity of the conclusions of such tests has been confirmed and verified by weather-exposure tests of the same materials.

It is now well recognized, by manufacturers and users alike, that sheet duralumin,* one of the most valuable materials of construction for aircraft, under some conditions, resulting either from fabrication or service or both, does not maintain its initial properties without impairment. This also applies to some of the other high-strength aluminum alloys. The change, in a few cases, has been found to be very pronounced indeed and,

*The term "duralumin" is used throughout as referring to the class of heat-treatable aluminum alloys in which the essential alloying elements are copper, magnesium, silicon, and manganese, and not to the product of any particular manufacturer.

as shown by the tensile properties, to consist in a marked lowering of the ductility accompanied by a somewhat smaller proportional decrease in the tensile strength. The very extensive and successful use of the high-strength aluminum alloys for aircraft and elsewhere has served in large measure to refute imputations which have been made at times concerning the general unreliability of this material. In general, experience has shown that most sheet duralumin under most conditions retains for years its initial strength and ductility unimpaired. With the increasing demands imposed upon the materials of modern aircraft construction, however, the question of permanence of such materials becomes one of increasing importance, hence the reason for the rather extensive investigation of the general subject of the permanence of duralumin sheet.

It has been definitely shown that the embrittlement of sheet duralumin referred to above is essentially a corrosion problem, the corrosive attack generally being intercrystalline in character. The most important factors afftecting the susceptibility of the alloy to this form of deterioration relate to the treatment rather than to the composition of the material. Heat treatment, consisting of quenching followed by aging, is essential in obtaining the high-strength properties of the duralumin type of alloy. Material which has been quenched in cold water is more resistant to the attack than if hot water is used as the quenching medium. Either one may be used with equal success in obtaining the desired high strength and ductility, however. Likewise, material aged at room temperature, after quenching, is more resistant than material aged at elevated temperature. The efficacy and value of coatings and other measures to protect the material against the attack depend upon circumstances. For severe marine conditions, aluminum, according to present knowledge is, by far, the most dependable coating. In considering the tests reported upon here these facts should be borne in mind since the test materials used were selected on the basis of the results of the previous series of tests.

Recently the question of the interrelation of externally applied stress and corrosion of metals has received very considerable attention. There are two general aspects to this problem. The effect of corrosive influence acting simultaneously with the stressing of a metal specimen by externally applied loadings, as in the determination of some of the mechanical properties of the metal, may be considered either from the standpoint of the effect of corrosion on the observed mechanical properties or, conversely, as the effect of the acting stress in accelerating the corrosion rate of the metal. McAdam, in his pioneer work on corrosion fatigue (Reference 2) has emphasized the first aspect of the problem. He has shown that the observed endurance limit of a metal when it is corroded simultaneously with the stressing of the specimen is very decidedly lower than the endurance limit obtained under ordinary conditions, that is, in air. Furthermore, he has shown that the lowering of the endurance limit which results when the specimen is corroded prior to the application of fatigue stress is not so pronounced as when corrosion accompanies fatigue. Recently (Reference 3) he has discussed the other aspect of the problem, to show how the rate of corrosion is influenced by the conditions of stress which may obtain. Moore (Reference 4) has confirmed McAdams' conclusions and shown the serious effect upon the endurance limit of duralumin in the form of thin-walled tubes when corroded simultaneously with the application of cyclic stress. Speller (Reference 5) has extended this type of work and shown that by the use of a corrosion inhibitor it is possible to prevent the lowering of the "air" endurance limit when the metal is subjected simultaneously to cyclic stress and corrosive influence.

In numerous instances, however, the second aspect of the stress-corrosion problem is, by far, the more important one. Removal and replacement of parts are frequently necessary solely because of deterioration resulting from corrosion. This seems to be particularly important in the aircraft industry where it is not only necessary that extreme care be taken in the initial selection of material but also in the inspection of such materials during service. Not only is it desirable to know the corrosion behavior of materials, as determined for ordinary circumstances, but also the manner and extent to which this behavior is affected by stress or other conditions which may be imposed upon the materials in service. In the summarizing of the results of the previous tests on the behavior of sheet duralumin exposed to the weather (Reference 6) it was stated:

> "Weather-exposure tests of the kind described here, while closely approximating service conditions, undoubtedly do not duplicate them. Tests are now in progress for the purpose of showing how the corrosion behavior of sheet duralumin may be affected by a stressed condition coincident with the corrosive attack."

It is with this aspect of the corrosion problem that this report is concerned.

It should be emphasized at the outset that the tests reported upon are primarily corrosion tests. Although in part of the work the material was subjected to cyclic flexural stresses, the primary aim has not been to determine the "life" of the material under such conditions but rather to show how and to what extent the corrosion behavior and hence the usefulness, is dependent upon the imposed conditions. The results of endurance or fatigue testing of the same material of course form a valuable background against which the present results may be viewed.

II. Material and Method of Test

1. Material

Nearly all of the tests were carried out upon a duralumin type of alloy commercially available under the name "17ST".*

*The materials were generously supplied by the Aluminum Company of America.

The average composition of the material used was:

Copper	4.1	per cent
Iron	.34	"
Silicon	.32	"
Manganese	.51	"
Magnesium	.61	"

The average tensile strength of the alloy, in the form of 14-gauge sheet, was as follows:

Ultimate tensile strength	59,000 to 61,000 lb./sq.in.
Yield point (stress for .006 in./inch extension under load)	40,000 to 42,000 lb./sq.in.
Elongation (2 inches)	20 to 23 per cent.

Some 16-gauge sheet was also used. Much of the material was "aluminum clad" sheet (Reference 7), a commercial material in which the coating forms an integral part of the finished sheet which is formed by rolling, into sheet form, a composite slab, consisting of duralumin with aluminum on the two opposite faces. The thickness of the two aluminum surface layers for the 14-gauge sheet used was approximately 5 per cent of the total thickness of the sheet. The tensile strength of the composite sheet is, of course, slightly less than that of a plain sheet of duralumin of the same thickness. The following properties are typical:

Ultimate tensile strength	55,000 lb./sq.in.
Elongation (2 inches)	19 to 22 per cent

A few tests were also carried out upon one of the high-strength aluminum alloys (51ST) which is free from copper and which was also used in a number of the previous tests.

2. Method

It is virtually impossible to study the accelerating effect of stress upon the corrodibility of metals in any other way than in the laboratory. In the present work, two methods were used: (a) the specimen was maintained under tension while being corroded and (b) the specimen was stressed repeatedly by flexure while being corroded. The specimens used were of the form of 10-inch tension bars, the principal dimensions of which are given in Figure 1. The tensile properties of the bar after corrosion periods of various durations were determined.

The corrosion method used in these tests as well as in the earlier ones in the investigation was the "wet-and-dry" or repeated immersion test used in the tests already reported upon. Such a test was considered to be more comparable to conditions which prevail in service, that is, occasional wetting followed by a period during which the surface is permitted to drain and possibly to dry, than a continual wetting of the surface would be, as in an immersion test.

a) Static tension

The device used for corroding the specimens while held in tensiom is shown in Figure 2. By means of tapped holes (not shown in the photograph) in the ends of the two end-pieces, into which suitable threaded fixtures could be screwed, it was an easy matter to hold the device in the testing machine, the Amsler tensile testing machine being used in these tests, and to apply a load of any desired amount. By means of the nuts on the two threaded bars, which fit rather loosely through the two end-pieces, it was possible to maintain the applied load as long as desired. All surfaces, except the central portion of the specimen under test, were then coated with paraffin and the entire device was used as the corrosion specimen in the apparatus used for the "wet-and-dry" method of corrosion testing. In brief, the method consisted in the immersion of the specimen at 15-minute intervals in a normal solution of sodium chloride (approximately 5.8 per cent by weight) to which had been added an amount of commercial hydrogen peroxide solution equal to 1/10 of the volume of the whole. The specimen was only momentarily immersed in the solution; for the greater part of the 15-minute period it was suspended horizontally in the air. After being corroded for the desired period, the specimen was removed from the holder and its tensile properties determined.

b) Repeated flexure

The apparatus, by means of which the corrosion of the specimens while they were being repeatedly stressed by flexure was carried out, is shown in Figures 4 and 5. The rather appropriate name of "wiggle machine" which has been applied to the apparatus, is very descriptive of its working.* The specimen was securely bolted at the ends to two uprights which could be rotated about their longitudinal axes and thus bend the specimen. The suspension for the uprights used was that usually referred to as a "Cardan support," which consists essentially of two X-shaped spring members, one above the other, placed 90° to each other. This method of suspension, which is sufficiently strong to transmit the necessary torque, permits freedom of motion transversely in all directions of the lower part of the upright. By this means, no significant stresses other than those resulting from bending were set up in the specimen.

The reduction gearing was designed so that by running the engine at its rated speed (1740 R.P.M.), the specimen was flexed at a rather slow rate, this being approximately 75 complete bends per minute.

In the calibration of the machine (which was done by a method suggested by Dr. L. B. Tuckerman) the principle of autocollimation of a beam of light was utilized. Directly in front

*The machine was constructed by J. Ludewig, mechanician, the essential features, especially the suspension of the uprights being suggested by Dr. L. B. Tuckerman, Engineer Physicist, Bureau of Standards.

of two totally reflecting prisms (spaced 2 inches apart) on the flat side of the specimen and "facing" each other, were placed two similar convex lenses. By such an arrangement a beam from a light source situated in front of one lens at a distance equal to the focal length of the lens will be reflected by means of the two prisms in succession and emerge from the second lens in a direction parallel to its initial path, when the test specimen is at rest and in an unstrained condition. A suitable horizontal scale can be used to locate the position of the returning beam. As the specimen is flexed, the spot of light travels back and forth on the scale. The data furnished by this set-up, together with a value of Young's modulus of elasticity for the material, are sufficient for the calculation of the maximum fiber stress of the flexing strip.*

At intervals of 15 minutes, the enameled cast-iron tank (T, in Figure 4) containing a sodium chloride solution similar to that used in the other tests, was automatically raised sufficiently high so as to immerse the specimen under test, the specimen being in the solution for approximately a minute. For purposes of comparison, a second specimen was suspended freely by the side of the stressed one and corroded under the same condi-

*The formula used for this was:

Maximum fiber stress (lb./sq.in.) = $\frac{tsy}{4fl}$, in which

t = thickness of the specimen,

f = focal length of the lens,

l = the distance between prisms (2 inches),

S = scale reading (total swing of spot across the scale),

Y = Young's modulus (10,000,000 lb./sq.in., assumed for duralumin).

tions. After being corroded for a predetermined period, the specimens were removed and their tensile properties determined. With a few of the specimens, however, the corrosive attack was continued long enough to result in failure of the specimen in the machine.

III. Results

The number of materials whose behavior could be studied has been limited. The choice was based upon the results of the previous tests. Since, according to these results, aluminum-coated duralumin appeared to be the most dependable material of the high-strength aluminum alloy class, this material was given preference over a number of others which might well have been studied. Likewise, since the heat treatment of duralumin sheet appears to be an important factor in determining its susceptibility to corrosive attack, this was borne in mind in selecting the materials for test. The results are summarized graphically in the accompanying diagrams. It should be borne in mind that the tensile properties given in each case are those of the corroded specimen and not those of a specimen cut from a larger corroded piece.

1. Corrosion Accompanied by Static Tension

The effect of corrosion on the tensile properties of duralumin while it is stressed in tension is shown in Figure 5. According to these results, duralumin sheet, coated with aluminum, maintains its initial properties unimpaired for corrosion periods as long as sixty days with an applied tensile stress as high as 20,000 lb./sq.in., which is approximately one-half the stress corresponding to the "yield point" as defined above. Even with a stress considerably higher than this (31,000 lb./sq.in.), the properties were not seriously impaired after forty days' attack.

On the other hand, a few days' attack of the unprotected alloy sheet corroded while simultaneously stressed in tension to approximately the same degree, was sufficient to cause a pronounced lowering of the tensile properties. In these tests, the material which had been heat-treated by being quenched in cold water, though far inferior to similar material having the aluminum coating, was superior to the sheet material which was heat-treated by being quenched in hot water. These results are in excellent agreement with the results of previous laboratory and exposure tests.

In Figure 6 is shown the microstructure of sheet duralumin after being corroded while in the stressed condition. It will be noted that the attack is, on the whole, typically intercrystalline in its nature. The effect of the applied stress has been to accelerate the corrosive attack but not to change its character in any essential respects.

2. Corrosion Accompanied by Repeated Flexure

The corrosive attack which occurred under these conditions was the most severe which has been encountered in any of the tests carried out. A corrosion test carried out in this manner is, indeed, a "searching" test and the dependability of a material showing superior corrosion-resisting properties under such conditions cannot well be questioned. The results are summarized in Figure 7. The examination of the microstructure (Figure 8) illustrates the fact that the characteristic features of the corrosive attack of the plain duralumin were not changed by the application of cyclic stress during the attack.

Discussion

It is often asserted that the corrosion behavior of a metal, as shown by atmospheric exposure tests, is not identical with the corresponding behavior in actual service. For many installations, for example, such as roofing, the results of exposure tests constitute as near an approach to actual service results, for the same weather conditions, as it is possible to obtain. In other cases, however, especially if the metal members be in a stressed state, the service corrosion behavior may differ quite considerably from that shown by simple exposure tests. Such might well be expected to be the case in aircraft materials.

Stress-corrosion tests must, perforce, be carried out as laboratory tests and, ordinarily, the best practical application that can be hoped for is by means of comparison tests carried out under the same laboratory conditions but on unstressed bars. If the results of such tests show no important difference in the behavior of a material when corroded with and without accompanying stress, it may safely be assumed that such will also be the case in service. Likewise, if the rate of corrosive attack of a metal is unquestionably accelerated by the application of stress during corrosion, such a condition may also be expected to obtain in service, although possibly not to the same degree, since in accelerated corrosion tests, the conditions are necessarily much more severe than those which will ordinarily prevail in service.

The results obtained in the foregoing tests in which the specimens were corroded while stressed in tension unmistakably show the relative merits of the two classes of material, plain duralumin sheet and the aluminum-clad duralumin sheet. The latter, when stressed one-half the "yield point" (20,000 lb./sq.in. stress for the coated sheet vs. 40,000 lb. for the "yield point" of duralumin sheet) showed no pronounced or significant change in its tensile properties after as much as sixty days' exposure to severely corrosive conditions. The same material stressed as high as 31,000 lb./sq.in., while being corroded, showed tensile properties after forty days' corrosion which were only slightly below the initial properties. According to the test results, protection of the exposed or cut edges of the aluminum-coated sheet is unnecessary.

On the other hand, the plain duralumin sheet, suitably heat-treated, when corroded under the same conditions showed a pronounced drop in the tensile properties after two days' attack and after twelve days' attack was very severely attacked. The same material when heat-treated by hot-water quenching, was still more severely attacked even under a somewhat lower stress.

It should be noted, however, that even in the unstressed condition, the corrosive attack of plain duralumin sheet was severe, and the <u>additional</u> effect produced by stressing the material in tension was considerably less than the effect of corrosion alone.

On the basis of the present test results, it may be questioned whether the accelerating effect of static tensile stress on susceptibility to corrosion need be considered very seriously if the conditions are mild enough to warrant consideration of the use of plain (uncoated) duralumin sheet as, for example, in inland service far removed from marine conditions. Certainly if the material can be given a coating which will not crack or flake under the stress acting, as illustrated by the aluminum-coated sheet, the effect of a static tensile stress, even of relatively high magnitude, may be considered entirely negligible so far as corrosion acceleration is concerned.

It is important to note that the effect of tensile stress, acting simultaneously with corrosion, was not such as to change the characteristic nature and was especially pronounced in the hot-water-quenched material. In the cold-water-quenched sheet the intercrystalline attack was in large measure obscured by pitting in the later stages of the attack.

The endurance limit of duralumin as determined by repeated flexure on material in the form of heat-treated sheet, such as was used in the present tests is, in all probability, close to 15,000 lb./sq.in. The corresponding value for aluminum-clad duralumin sheet of the same thickness, as determined in the same way, is somewhat lower by several thousand pounds per square inch.*

In the present tests of corrosion accompanied by repeated flexural stress, the stress imposed on the duralumin specimens ±10,000 lb./sq.in., was well below the stress allowed for in the design of girders and other structural members in aircraft construction. It was also considerably below the probable value of the endurance limit as determined by the method of repeated flexure and in the absence of any (intentional) corrosive conditions. The applied stress was slightly above the so-called "corrosion-fatigue" limit of duralumin which, according to McAdam (Reference 8) is, in fresh water, ±7,000 to 9,000 lb./sq.in. and, in salt water, ±6,000 to 8,000 lb./sq.in.

The relatively long "life" shown by the cold-water-quenched duralumin sheet may be somewhat misleading unless due and care-

*Bureau of Standards investigation. Work in progress on the endurance limit for the aluminum-coated sheet indicates that it apparently lies somewhat above 10,000 lb./sq.in.

ful consideration is given to the tensile properties, both tensile strength and ductility, of the material during the progress of the test. During the early stages, the corrosive attack showed its greatest effect in the lowered ductility; this dropped to a very low value and remained almost unchanged during the latter half of the test. The tensile strength, however, continued to drop, with but few exceptions, throughout the latter part of the test. The effect of the imposed stress in accelerating the corrosive attack is best shown by a comparison of the tensile strengths of the two sets of specimens, stressed and unstressed, rather than by the ductility. The reduction in tensile strength is indicative of the reduced cross section of the material, that is, the depth to which corrosion has penetrated, whereas the ductility is apparently influenced more by the manner of the corrosive attack. During the early stages of the corrosion of the cold-water-quenched sheet, the intercrystalline attack predominated, and a penetration of the metal by this method, even if only to a slight depth, was sufficient to reduce the ductility to a relatively low value. As the corrosion was continued, however, the attack assumed the form of pitting and as the cross section was progressively decreased by the deepening of the pits, the tensile strength decreased in like manner. Although, as indicated by the number of bends which the specimen withstood for the severe conditions used (±10,000 lb./sq.in. + severe corrosion) the "life" of the material might be stated to be in the neighborhood of 3,000,000 complete bends, it is evident from a consideration of the progressive decrease in the tensile properties (Figure 5) that the "life" for which the material could be recommended for these conditions would be decidedly less than this value.

Since the hot-water-quenched duralumin is more susceptible to the intercrystalline type of attack, this continued throughout as the predominating form of corrosion. As shown by the micrographs of the corroded specimens (Figure 8) a relatively deep penetration of the metal together with failure of the specimen resulted relatively early.

The aluminum-clad duralumin sheet in all cases was stressed to a degree much higher than the stress corresponding to the endurance limit of this material. In spite of this fact, however, a "life" of 24 to 32 days was shown by this material under the very severely corrosive conditions which were imposed upon it. This life was, of course, directly determined by the behavior of the coating. Not until failure of the coating occurred was there any noticeable attack of the underlying duralumin. The examination of the microstructure of the tested specimens suggests (Figure 9) that the fatigue stresses played a much more important part in the failure than did corrosion. The cracks which formed in the aluminum surface layer and gradually extended into the underlying duralumin as the flexing of the bar was continued, were very similar in appearance to the corresponding cracks which form in the same material when it is repeatedly stressed in the absence of a corrodent, as in the air. In many cases the cracks showed a definite tendency to form at an angle of 45° with the surface, a feature in which corrosion would play little or no part. The rate at which the cracks progressed may, of course, have been affected by the corrodent. It is of interest to note that the characteristic intercrystalline type of corrosive attack was not at all pronounced in the specimens.

Although the tests which are reported above on the continued effect of corrosion and flexural stress have given valuable indications as to the relative value of the two types of material tested and hence served their purpose in the general investigation of which they form a part, it is believed that the tests still in progress will serve to emphasize this much more strikingly. In these tests a lower stress, more nearly comparable with the endurance limit and the "corrosion-fatigue limit" of the material is being used. These results will be given in a supplementary report.

It is evident that when a corrosive attack is accompanied by cyclic stress, the relative importance of the effect produced by each will, for a given stress value, be largely dependent upon the frequency of the stress cycle used. McAdam has discussed some aspects of this phase of the general stress-corrosion problem (Reference 3). Since the present tests were primarily <u>corrosion</u> tests, the corrosion factor was made the predominating one by using a relatively low frequency in the application of the flexural stress. Such a combination of the corrosion and the stress factors as this one is also believed to be more truly representative of service conditions in which the limit of the usefulness of a material is determined by corrosive influences rather than by the stress acting than would similar tests in which the stress factor predominated, such as would be the case if the tests more nearly approximated fatigue tests.

Summary

1. As part of a general study of the corrosion-embrittlement of sheet duralumin, tests were carried out to show how and to what extent the corrosion behavior of this material is affected by stress accompanying the corrosive attack. The effect of both static tension and repeated flexural stress was determined, the change in the tensile properties of corroded specimens being used as a measure of the effect produced by stressing the bars while corrosion, by the "wet-and-dry" method in a sodium chloride solution, was going on.

2. The corrosion of plain duralumin sheet material was accelerated by a static tensile stress, somewhat below the "yield point" of the material, the increase in the corrosive attack with hot-water-quenched material being greater than that with cold-water-quenched duralumin. In both cases, however, the effect of corrosion alone (unstressed specimens) was very consider-

ably greater than the increase resulting from stressing the specimen during corrosion. In the case of aluminum-clad duralumin, the corrosive attack with both stressed and unstressed specimens was exceedingly slight even for long corrosion periods.

3. Corrosion accompanied by repeated flexural stressing of the specimen constitutes a very "searching" corrosion test for duralumin. Plain duralumin sheet was severely attacked, especially the hot-water-quenched material. The early stages in the attack result in a pronounced lowering of the ductility, the later stages in a drop in the tensile strength. The aluminum-clad duralumin, even when stressed, during corrosion, to a point very much above its endurance limit, gave results consistent with its superior behavior under other conditions. The conditions used were exceptionally severe; further tests more in keeping with assumed service conditions are in progress.

4. Corrosion accompanied by stress did not change the characteristic feature of the corrosive attack of duralumin, that is, its intercrystalline nature, as shown by specimens corroded in an unstressed condition and in material corroded by exposure to the weather. In the material of higher corrosion resistance (cold-water-quenched duralumin) the intercrystalline attack prevails in the early stages and results in a lowered ductility. In the later stages, pitting appears to obscure the intercrystalline attack and as the pits deepen, the tensile strength is pro-

gressively lowered. In the hot-water-quenched material the intercrystalline type of attack is prominent throughout. Aluminum-clad duralumin sheet corroded while being repeatedly stressed by flexure, the stress being considerably above the endurance limit, showed the same characteristic fatigue cracks originating in the aluminum surface layer, as form in similar tests carried out in absence of a corrodent. No pronounced evidence of corrosion, as shown by a characteristic intercrystalline attack, was observed under these conditions.

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Legends for Figures

Fig. 1. Dimensions of specimens of sheet material used in the stress-corrosion tests.

Fig. 2. Device for maintaining a specimen under tension during corrosion, with specimen in position. The assembled device after covering the surface with paraffin, except that of central part of the specimen, is used as the corrosion "specimen."

Fig. 3. Side view of the apparatus used for corroding a specimen while it is repeatedly stressed by flexure.
M, motor; W, W', worm gears; C, cam; T, tank containing solution which is raised at 15-minute intervals; S, specimen; U, uprights with the Cardan suspension at the top inside the housing; H; B, ball bearing.

Fig. 4. Top view of the apparatus of Figure 4.
H, H', housings within which are the Cardan suspensions for the uprights; R, reciprocating slide; D, rotatory drive actuated by the worm drive shown in Figure 4.

Fig. 5. Effect of static tension, acting simultaneously with corrosion, on the tensile properties of sheet duralumin, both plain and aluminum-clad.
The corrosion was carried out by the wet-and-dry method by immersion at 15-minute intervals in a sodium chloride-hydrogen peroxide solution.

Fig. 6. Microstructure of 16 gauge sheet duralumin corroded while under tension, x 90.
Longitudinal sections perpendicular to the flat side of the specimen, unetched, in all cases.
a, cold-water-quenched duralumin sheet after 4 days' attack; 30,800 lb./sq.in. tensile stress.
b, same as a after 12 days.
c, hot-water-quenched duralumin sheet after 4 days' attack; 19,800 lb./sq.in. tensile strength.
d, same as c after 12 days.

Fig. 7. Effect of repeated flexural stress, simultaneous with corrosion, on the tensile properties of sheet duralumin, both plain and aluminum-clad. Results are also given for another high-strength aluminum alloy, 51ST. The corrosion was carried out by the wet-and-dry method by immersion at 15-minute intervals in a sodium chloride-hydrogen peroxide solution.

Fig. 8. Microstructure of 16 gauge sheet duralumin corroded while being repeatedly stressed by flexure, 10,000 lb./sq.in. maximum fiber stress, x 90.

Longitudinal sections perpendicular to the flat side of the specimen, unetched, in all cases.

a, hot-water-quenched sheet duralumin after 1 day's attack.

b, hot-water-quenched sheet duralumin after 4 days' attack.

c, similar material, unstressed, after 5 days' attack.

d, cold-water-quenched duralumin sheet after 3 days' attack.

e, similar material after 9 days' attack.

Fig. 9. Microstructure of aluminum-clad duralumin sheet after corrosion accompanied by repeated stressing by flexure, x 90.

Longitudinal sections perpendicular to the flat side of the specimen, unetched, in all cases.

a, maximum stress ±20,000 lb./sq.in., for 24 days, total number of complete bends 2,477,000. Note the cracks which have formed in the aluminum layer.

b, comparison specimen, unstressed, corroded under same conditions as a. The thickness of the aluminum coating is indicated.

c, same stress as a, 32 days, total number of complete bends 3,080,000. The specimen failed during the "run." Note the 45° trend of the cracks.

d, maximum stress ±31,250 lb./sq.in., for 6 days. The specimen failed during the "run." Total number of complete bends was 524,130.

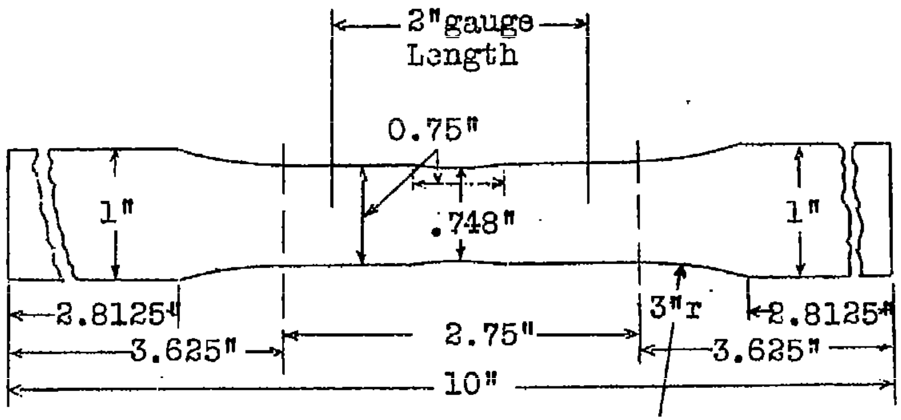
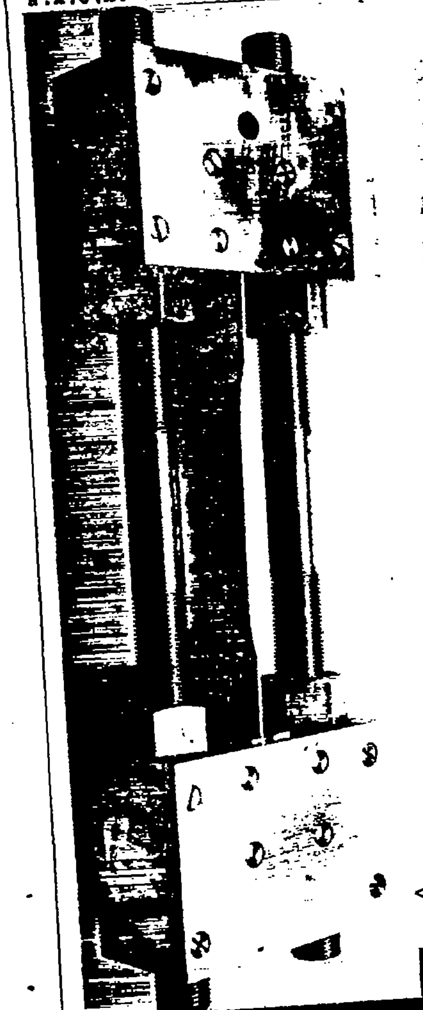


Fig.1



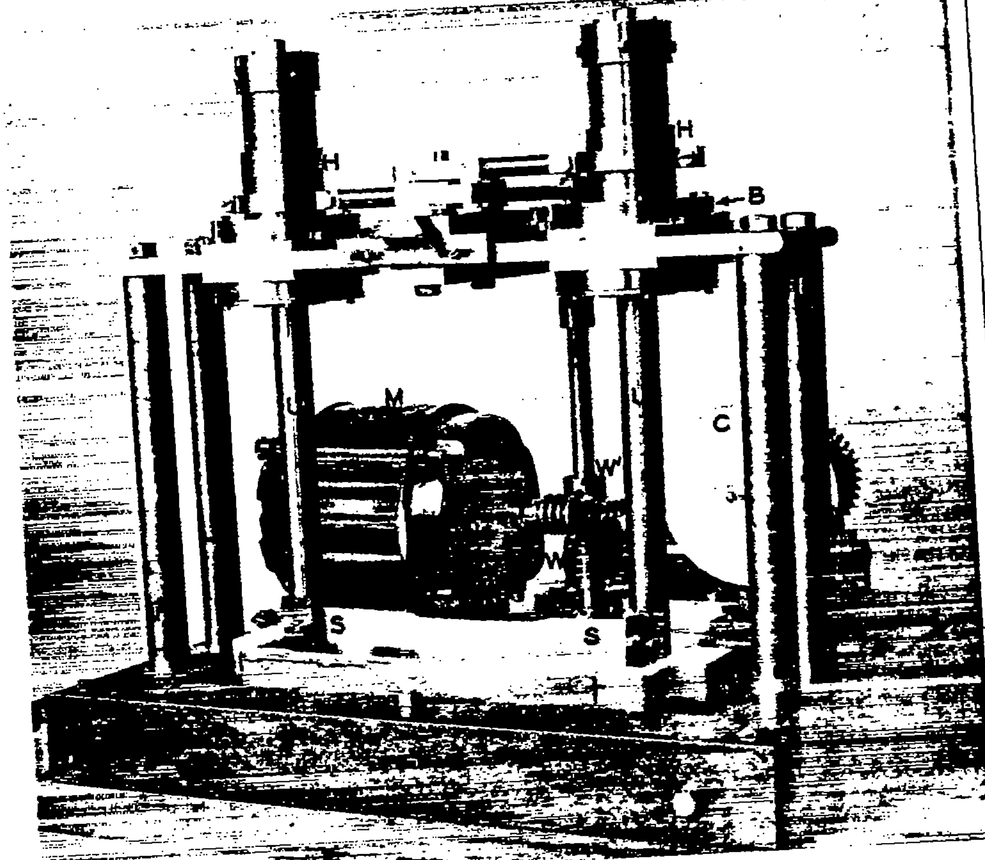
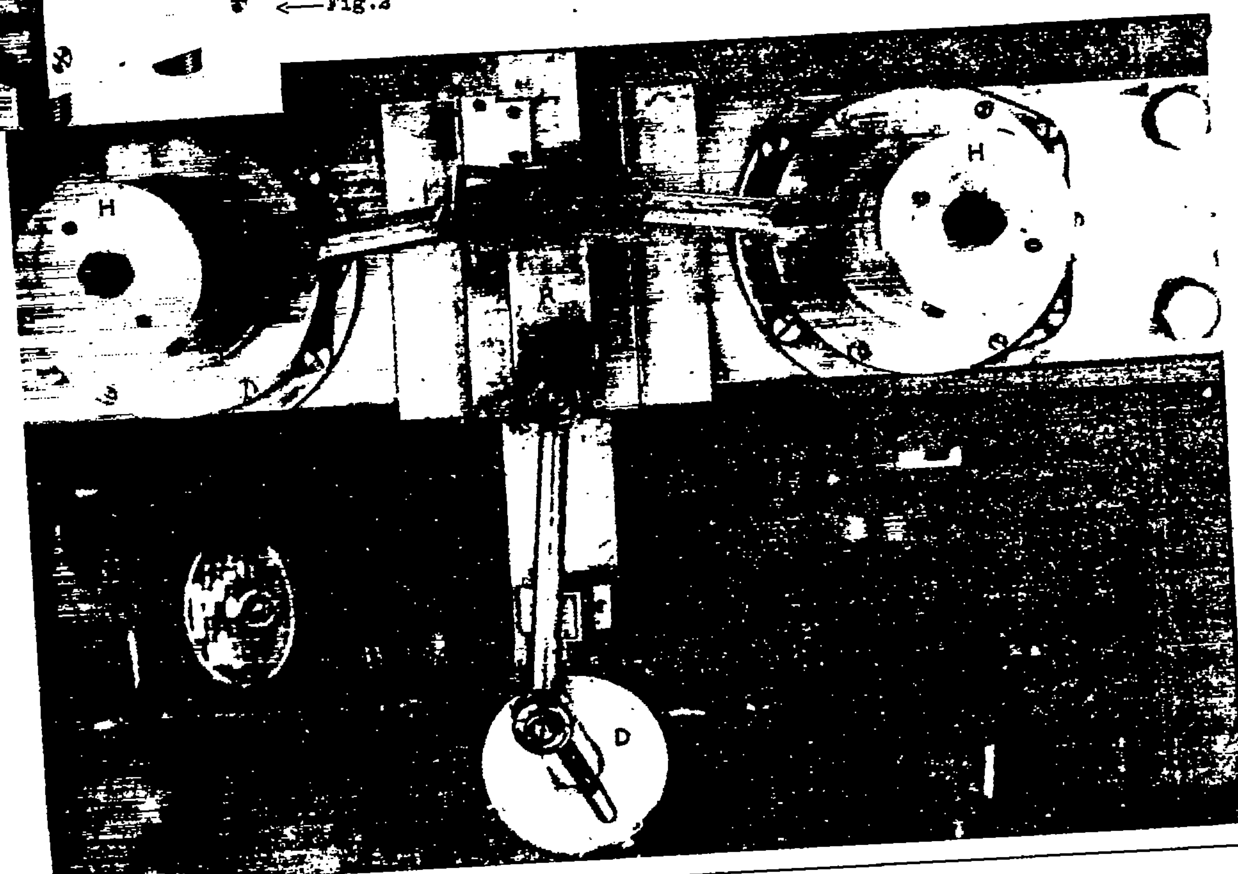


Fig.3

←Fig.2



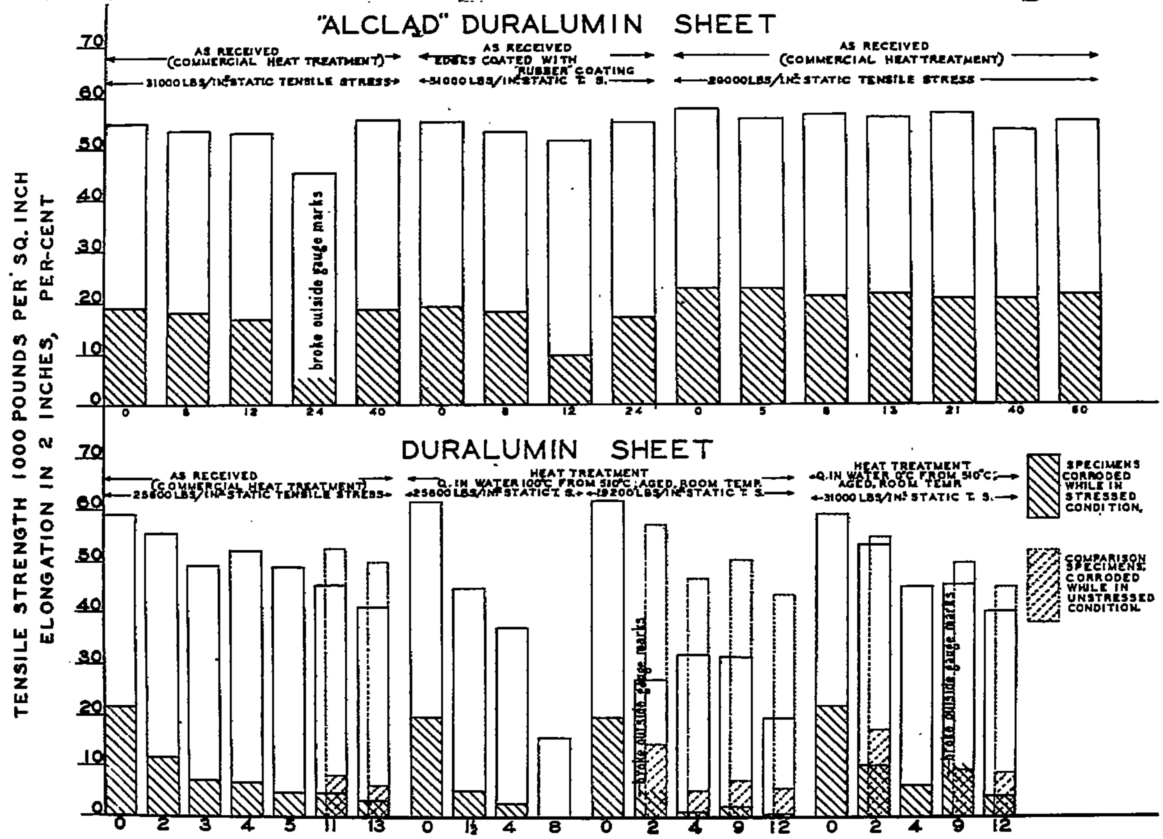

"ALCLAD" DURALUMIN SHEET
DURALUMIN SHEET
TENSILE STRENGTH 1000 POUNDS PER SQ. INCH
ELONGATION IN 2 INCHES, PER-CENT
SPECIMENS CORRODED WHILE IN STRESSED CONDITION.
COMPARISON SPECIMENS CORRODED WHILE IN UNSTRESSED CONDITION.
DAYS OF CORROSION

Fig. 5

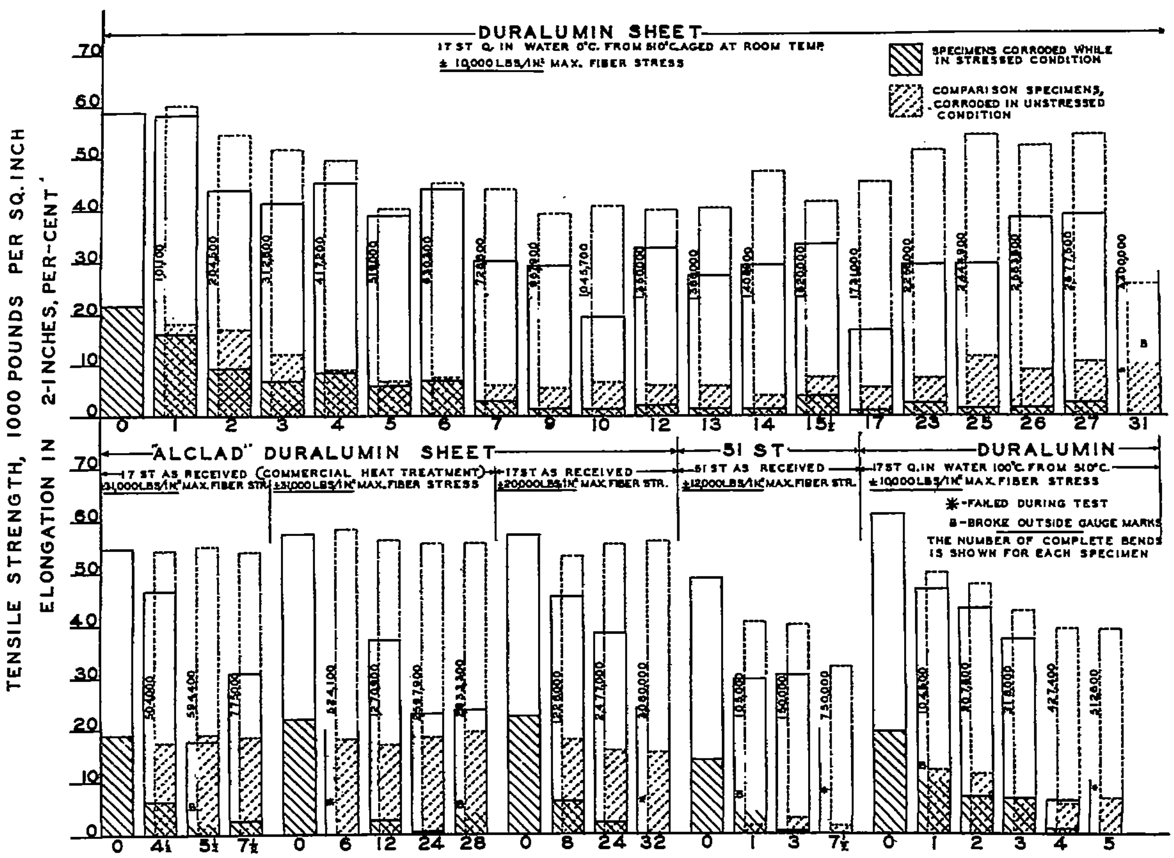

DURALUMIN SHEET
"ALCLAD" DURALUMIN SHEET
51 ST
DURALUMIN
TENSILE STRENGTH, 1000 POUNDS PER SQ. INCH
ELONGATION IN 2-INCHES, PER-CENT
SPECIMENS CORRODED WHILE IN STRESSED CONDITION
COMPARISON SPECIMENS, CORRODED IN UNSTRESSED CONDITION
*-FAILED DURING TEST
B-BROKE OUTSIDE GAUGE MARKS
THE NUMBER OF COMPLETE BENDS IS SHOWN FOR EACH SPECIMEN
DAYS OF CORROSION (APPROXIMATE)

Fig. 7

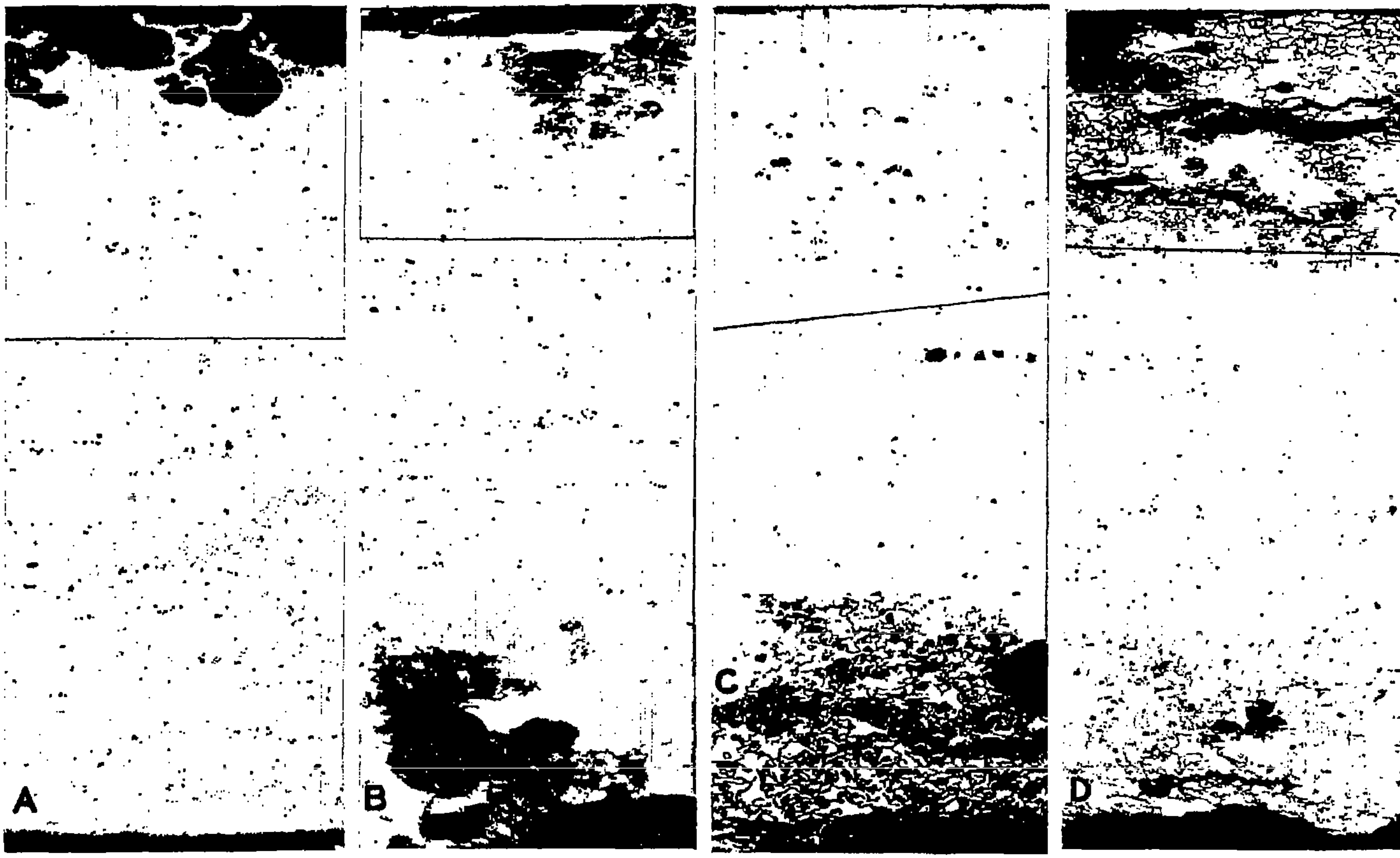
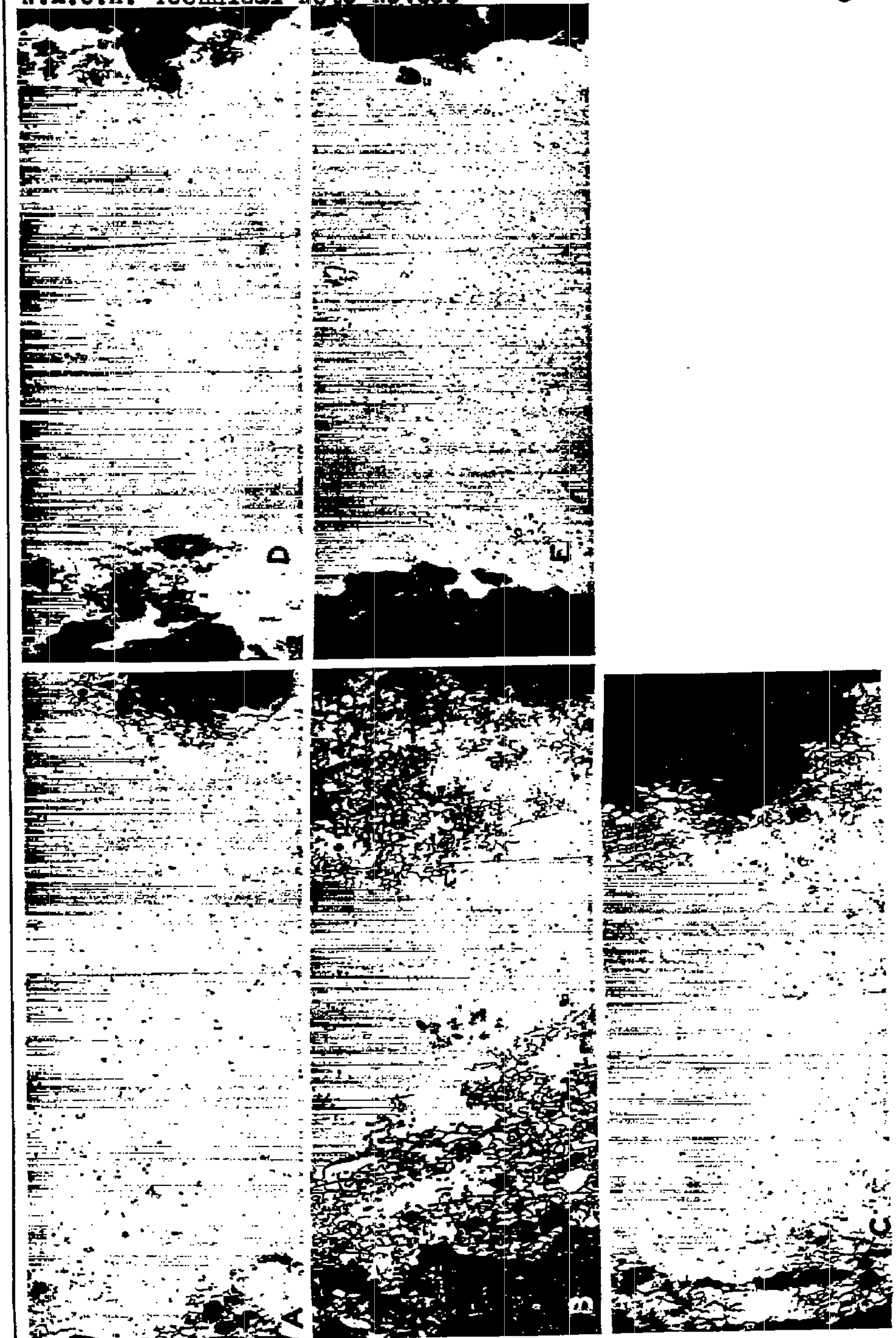


Fig.6

Fig.8



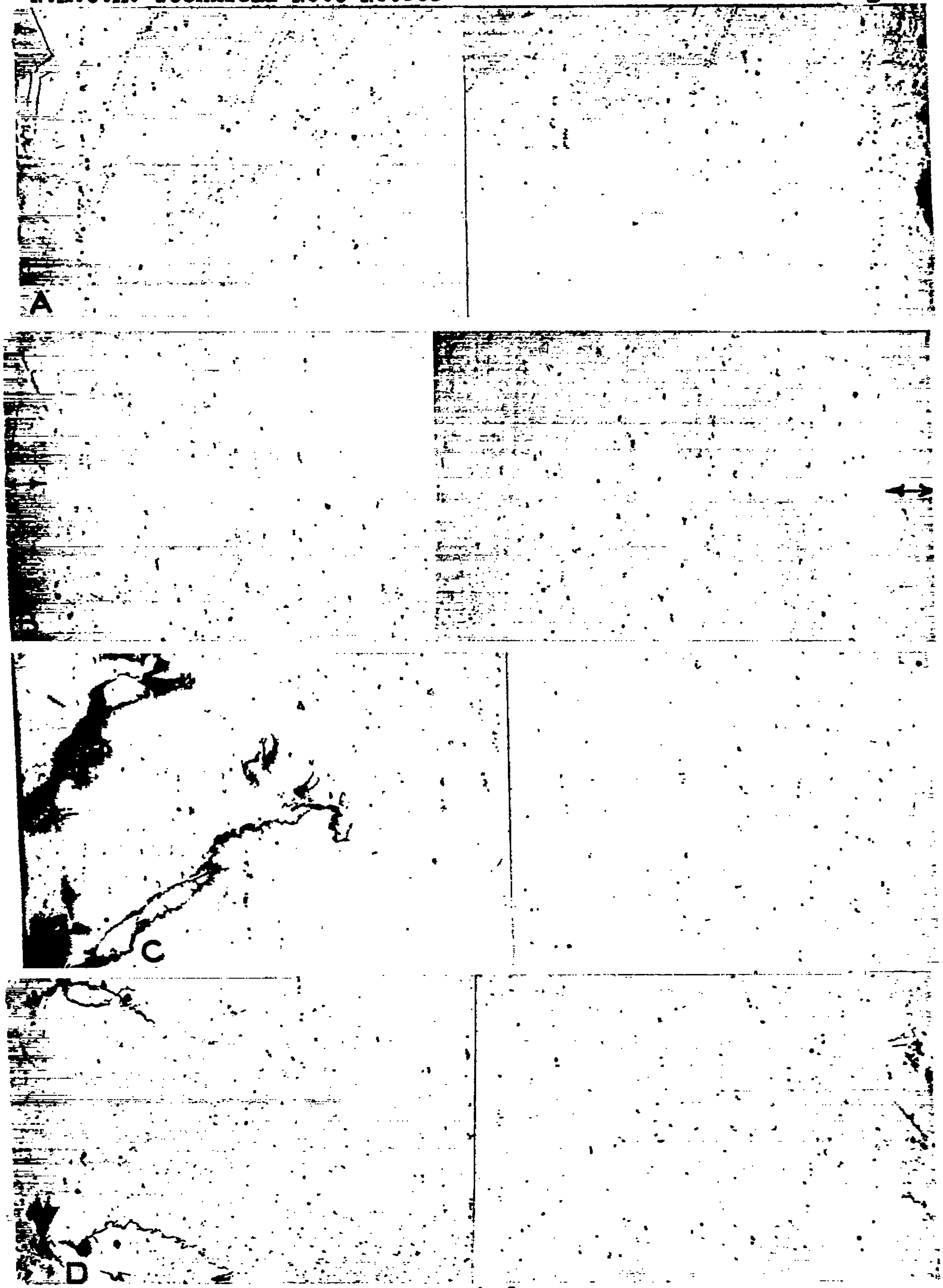


Fig.9